Final Report 2015

Plug-In Hybrid Urban Delivery Truck Technology Demonstration

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Recipient: South Coast Air Quality Management District

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This report does not contain any proprietary, confidential, or otherwise restricted information.

1. EXECUTIVE SUMMARY

The I-710 and CA-60 highways are key transportation corridors in the Southern California region that are heavily used on a daily basis by heavy duty drayage trucks that transport the cargo from the ports to the inland transportation terminals. These terminals, which include store/warehouses, inland-railways, are anywhere from 5 to 50 miles in distance from the ports. The concentrated operation of these drayage vehicles in these corridors has had and will continue to have a significant impact on the air quality in this region whereby significantly impacting the quality of life in the communities surrounding these corridors. To reduce these negative impacts it is critical that zero and near-zero emission technologies be developed and deployed in the region. A potential local market size of up to 46,000 trucks exists in the South Coast Air Basin, based on near-dock drayage trucks and trucks operating on the I-710 freeway. The South Coast Air Quality Management District (SCAQMD), California Air Resources Board (CARB) and Southern California Association of Governments (SCAG) — the agencies responsible for preparing the State Implementation Plan required under the federal Clean Air Act — have stated that to attain federal air quality standards the region will need to transition to broad use of zero and near zero emission energy sources in cars, trucks and other equipment (Southern California Association of Governments et al, 2011).

SCAQMD partnered with Volvo Trucks to develop, build and demonstrate a prototype Class 8 heavy-duty plug-in hybrid drayage truck with significantly reduced emissions and fuel use. Volvo's approach leveraged the group's global knowledge and experience in designing and deploying electromobility products. The proprietary hybrid driveline selected for this proof of concept was integrated with multiple enhancements to the complete vehicle in order to maximize the emission and energy impact of electrification. A detailed review of all technologies included in the demonstrator is presented in this report.

The project was completed in July 2015 with a final demonstration of the concept vehicle on a simulated drayage route around Volvo's North American headquarters in Greensboro, NC. The route included all traffic conditions typical of drayage operation in Southern California as well as geofences defined to showcase the zero emission capabilities of the truck. The demonstrator successfully completed four consecutive trips with a gross combined vehicle weight of 44,000 lb., covering approximately 2 miles out of a total distance of 9 miles per trip in the Zero Emission (ZE) geofence.

This vehicle is expected to use approximately 30% less fuel than a typical drayage truck in daily operation, and it is designed to allow full electric operation whenever operating in a marine terminal in the ports of Los Angeles / Long Beach.

A paper study on the feasibility of expanding the capabilities of the plug-in hybrid concept developed as part of this project was also delivered as an addendum to the regular progress reports.

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List of Acronyms

ACM	After-treatment Control Module
AMT	Automated Manual Transmission
BSFC	Brake Specific Fuel Consumption [g/kWh]
BMU	Battery Management Unit
BTE	Brake Thermal Efficiency
Cd	Coefficient of drag
CFD	Computational Fluid Dynamics
CICU	Charging Interface Control Unit
DCU	DC/DC Control Unit
DPF	Diesel Particulate Filter
ECU	Electronic Control Unit
EECU	Engine Electronic Control Unit (EMS)
EM	Electric Machine
EMaP	Energy Management Panel
EMS	Engine Management Unit (EECU)
EHPS	Electro-Hydraulic Power Steering
ESS	Energy Storage System
GCW	Gross Combined Weight
GHG	Greenhouse Gas
GPS	Global Positioning System
GSP	Global Simulation Platform
GVW	Gross Vehicle Weight
HPCU	Hybrid Powertrain Control Unit
ISAM	Integrated Starter-Alternator Motor
MCU	Motor Control Unit
NO_X	Nitrogen Oxide
PTO	Power Take-Off
PUCU	Hybrid (cooling) Pump Control Unit
RPM	Revolutions per Minute
SCR	Selective Catalytic Reduction
TECU	Transmission Electronic Control Unit
VGT	Variable Geometry Turbocharger

2. PROJECT DESCRIPTION

The objective of this project was to develop, build and demonstrate a prototype Class 8 heavy-duty plug-in hybrid drayage truck with significantly reduced emissions and fuel use. The truck features a 6x2 Mack chassis at 60,000 GCW with the proprietary hybrid driveline, a new energy optimized battery, external charging interface and newly developed energy management and control systems suitable for port drayage application. Using hybrid trucks for drayage application (and other local and regional haul applications) can reduce emissions and lowers fuel use significantly. By utilizing plug-in hybrid technology, fully zero-emission electric mode is possible for limited distances at low speeds, such as in a predetermined zero emission geofence. The integration of a plug-in hybrid powertrain with downsized engine (11L in lieu of 13L), along with several improvements to the complete vehicle efficiency are expected to add up to approximately 30% improvement in fuel economy in a drayage cycle containing a mix of the driving patterns described in the report “Characterization of Drayage Truck Duty Cycles at the Port of Long Beach and Port of Los Angeles”. Using clean electricity from the southern California grid to externally recharge the hybrid battery and offset the least efficient operating points of the engine is also expected to result in approximately 30% reduction of greenhouse gas (GHG) emissions.

The project delivered a working prototype plug-in hybrid truck along with a first evaluation of the efficiency and emission potentials of the technology.

In addition to reduced fuel usage and emissions, the integration of the hybrid powertrain with multiple vehicle efficiency improvements is expected to yield the following benefits:

- Reduction of regulated emissions
- Displacement in the consumption of fossil fuel
- Reduced brake wear
- Reduced noise emissions
- Equivalent or better dynamic performance

The table below summarizes the high-level project milestones for the development and demonstration of the class-8 drayage PHEV demonstrator.

Milestone Status Report			
Milestone	**Estimated Completion**	**Actual Completion**	**Comments**
Task 2 complete - Develop Requirements and Specifications	Dec-12	Jan-13	Complete
Tasks 3.2 & 3.3 complete - prelim. Concept selection	Feb-13	Apr-13	Complete
Task 3 complete - Concept Selection and Hardware Development	Jul-13	Aug-13	Complete

Task 4.3 complete - virtual optimization	Aug-13	Apr-15	Delayed to Jan-15, no impact on timeline
Task 4.2 complete - software ready for prototype vehicle	Mar-14	Mar-14	Complete
Task 4 complete - Control System Development	Jul-14	Mar-15	Delayed due to late commissioning
Task 5.1 complete - ESS solution defined	Jul-13	Jul-13	Complete
Task 5.2 complete - Verification plan	Oct-13	Apr-15	Delayed to Dec-14, no impact on timeline
Task 5 complete - Component Validation	Jan-14	Mar-14	Delayed to Mar-14, no impact on timeline
Task 6.2 complete - packaging study	Jan-14	Mar-14	Delayed to Mar-14, no impact on vehicle build
Task 6 complete - Prototype Vehicle Build	Jul-14	Apr-15	Delayed to Jan-15 upon extension of project
Task 7 complete - Vehicle Testing & Demonstration	Sep-14	Jul-15	Delayed to Jul-15 upon extension of project
Task 8 complete - Study of Electrified Road Systems	Sep-14	Jul-15	Delayed to Jul-15 upon extension of project
Final Report complete	Dec-14	Jul-15	Delayed to Jul-15 upon extension of project

In order to achieve these milestones, the project team contained the following tasks.

Task 1 - Program Management and Planning

This task consisted of all aspects of program and project management, communication, and reporting to the project team including developing and maintaining a project schedule. The project team included expertise in all technical areas covered by this concept truck. External engineering services were secured to minimize impact of resource internal limitations in some critical path activities, such as virtual assembly and design.

The complete technical content of the concept truck was reviewed and finalized in a face-to-face design review meeting held with the full team in Volvo's Vehicle Engineering division in Greensboro, NC in August 2013.

The global Volvo technical team met weekly to review and discuss any open issues, as well as plan work to secure upcoming milestones. It included representatives from all key engineering groups, e.g. vehicle engineering, powertrain engineering, complete system simulations, etc. Regular web meetings were held between Volvo and SC AMQD to review the status of the project and discuss open issues.

The Volvo project manager visited the Ports of Los Angeles and Long Beach during fall 2013 to gain better first-hand understanding of drayage operation from various perspectives, including Port Authority, Air Quality Management, drayage fleet operator, community impact, etc. This was a good opportunity to document some of the key duty cycle features to share with the team and help share the knowledge of local constraints and unique requirements. The pictures below illustrate some of the typical characteristics of the drayage operation captured in the reference duty cycle.



Task 2 – Develop Requirements and Specifications

2.1 The goal of this sub-task was to characterize the use-profile of Class 8 trucks in port drayage applications and to develop detailed operational requirements for the concept truck. These requirements were documented in a project prerequisites document which guided the concept selection throughout the project to identify the suite of technologies best suited to reduce energy usage in the drayage application. These detailed requirements and baseline vehicle definition described in Task 6 were frozen in late 2013.

The characterization of port drayage operation was initially based on the documentation of the application by TIAX in Case D0529. The speed profiles identified were used as a basis to quantify the performance requirements of the concept truck. The team also included other technical requirements identified from previous R&D studies performed in the area of electromobility.

This study also included a review of several possible vehicle configurations. As there are many different transaction types in the port drayage vehicle operations (ex. inbound, outbound, loaded container, empty container, no container, etc…) as well as little repeatability from day-to-day operations, there is a need to try to rationalize what transaction types are used for developing the definition of each of the duty cycles. The three main vehicle configurations deemed necessary at the minimum for supporting the simulation work are:

- Tractor + Trailer Chassis with Loaded 40 foot Container (from port terminal to customer or reversed).
- Tractor + Trailer Chassis with Empty 40 Foot Container (typically from customer back to the port terminal).
- Tractor Only or Bobtail (first pick-up of the day to port terminal or customer)

These three configurations should cover the range of operations needed to help determine the energy needs required to meet the objectives. Even though the drayage application primarily focuses on a 60,000lb max GCW, the vehicle was designed to be capable of transport missions up to 80,000lb.

2.2 The goal of this sub-task was to define a vehicle duty-cycle to be used in complete vehicle simulations. This test cycle should take into account the main attributes of the Class 8 port drayage truck operations such as, for example, the road profile, the temperature, the payload, the various speed profiles, and acknowledge idle operation.

Detailed duty-cycles were developed and used in complete vehicle simulations. They are based on the speed profiles published in the TIAX report above to be compatible with the simulation tools, enhanced with an altitude profile which represents the features identified in the area of operation as described in the characterization study performed by TIAX.

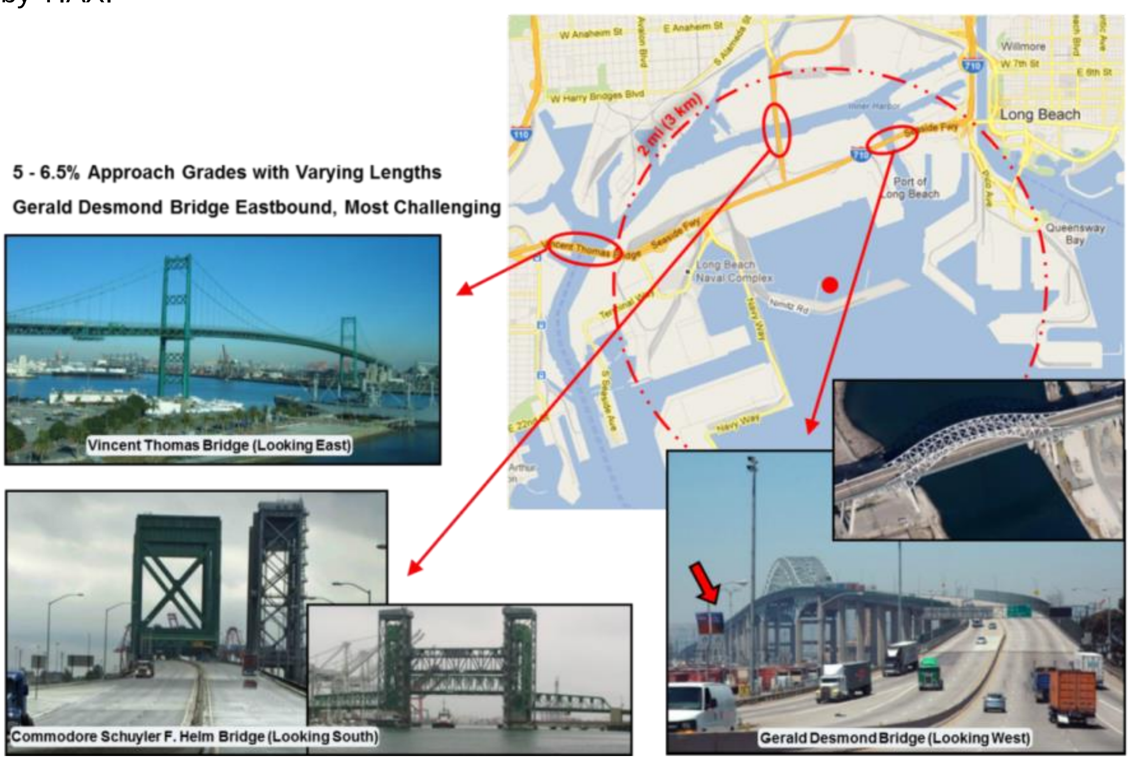


Figure 1 – Detailed Analysis of Road Features in 'Near Dock' Duty Cycle

For this project the focus was on the “Near Dock” operation since this is where the initial benefits of the plug-in driveline are expected to be the greatest, and where the requirements on zero-emission operation are the most critical. An initial duty cycle was created for this route using the Gerald Desmond Bridge which is the most challenging feature for energetic considerations. An arbitrary turn-by-turn route was defined to allow the team to simulate a typical near-dock operation and to estimate the amount of idle operation. See overview below.

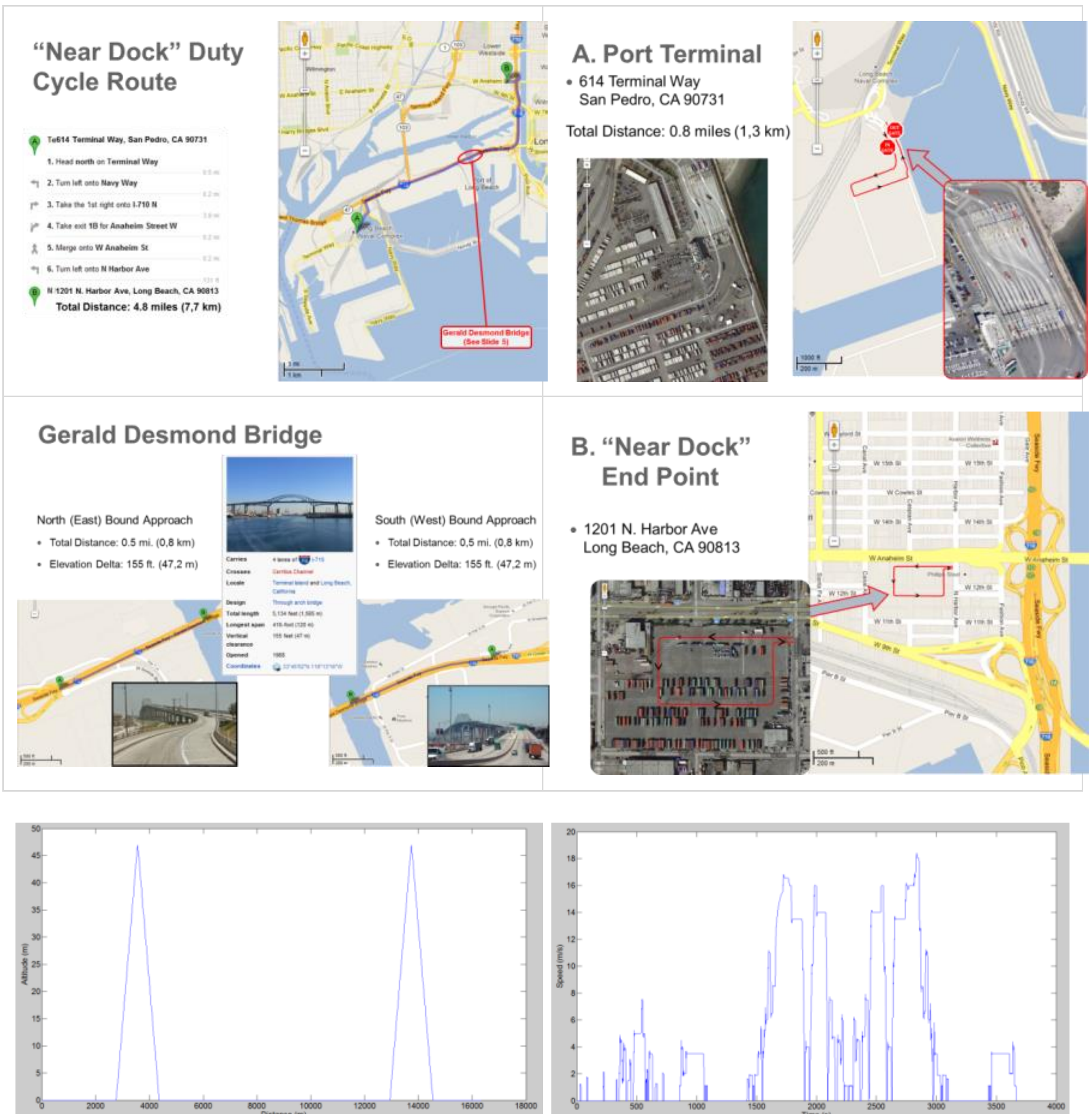


Figure 2 – Custom Altitude and Speed Profiles Developed for Simulation

All input data so far had been gathered from previous studies, and we observed from simulation results that the speed and altitude profile of the roads had a major impact on the performance of the hybrid vehicle. Hence, it was decided to obtain more detailed information about these routes by monitoring drayage fleet trucks in revenue service as well as by collecting additional data *in situ*.

A meeting was organized with the fleet manager of a large drayage fleet in the ports of Los Angeles/Long Beach, which helped gain deeper understanding of the drayage duty cycles, fleet usage, and driver perspective as well as preferred truck configurations. These inputs were valuable in understanding the most desirable features of the drayage vehicles and in finding ways to make the most effective PHEV drayage truck.

It was decided to instrument 3 Mack customer drayage trucks so that more data can be collected regarding the vehicle speed, location, torque, engine speed, as well as some proprietary signals. A detailed list of signals to be recorded was created and the necessary instruments for recording were secured and tested. In late 2013 a team visited Los Angeles to instrument the vehicles, and recorded detailed information on the main corridors identified within the typical drayage operation. Data was recorded in each of the trucks for approximately six weeks.

The data was retrieved and analyzed to refine the reference duty cycles used in simulations, along with any assumptions made at the beginning of the project, e.g. percentage of idle time in a typical shift. The main updates to the initial duty cycle included refined altitude profile for the primary drayage routes identified and increased idle time in the reference cycle to better match the vehicle speed distribution observed on customer vehicles.

This data analysis also allowed us to see where the trucks monitored were operating on a daily basis and what kind of power levels their loads would require. By using an application called “GPS Visualizer” we were able to map out all the duty cycles. This allowed us to gain information on specific areas of the port of Long Beach and also specific warehouses on the outskirts of the city. One early conclusion was that there was not one simple back and forth “run” that the trucks used consistently. Another important finding was the need to consider the impact of congestion on route selection. We found that the Commodore Helm 47 bridge was used most often followed by the Vincent Thomas 47 bridge. This was not expected, but it showed the drivers probably preferred to take Alameda Street instead of the Gerald Desmond Bridge to take advantage of a direct route with reliable traffic patterns while avoiding heavy traffic. The PHEV concept was designed according to present preferred routes but if circumstances or routes change the truck is capable of adapting to a new route without comprising its performance.

After mapping out each duty cycle we took a closer look into the power consumption during a normal day of operation. We overlaid speed data onto the GPS maps we created to determine how fast the truck was traveling inside the ports and also the top speed these trucks reached on the highway. This is critical in order to determine whether the electric drive system would be sufficient to move a loaded cargo box with the port in Zero Emission mode. We observed that the maximum power produced by the trucks’ engine while inside the port area was around 100 HP, which is close to the continuous power capability of the electric drive system selected for this truck.

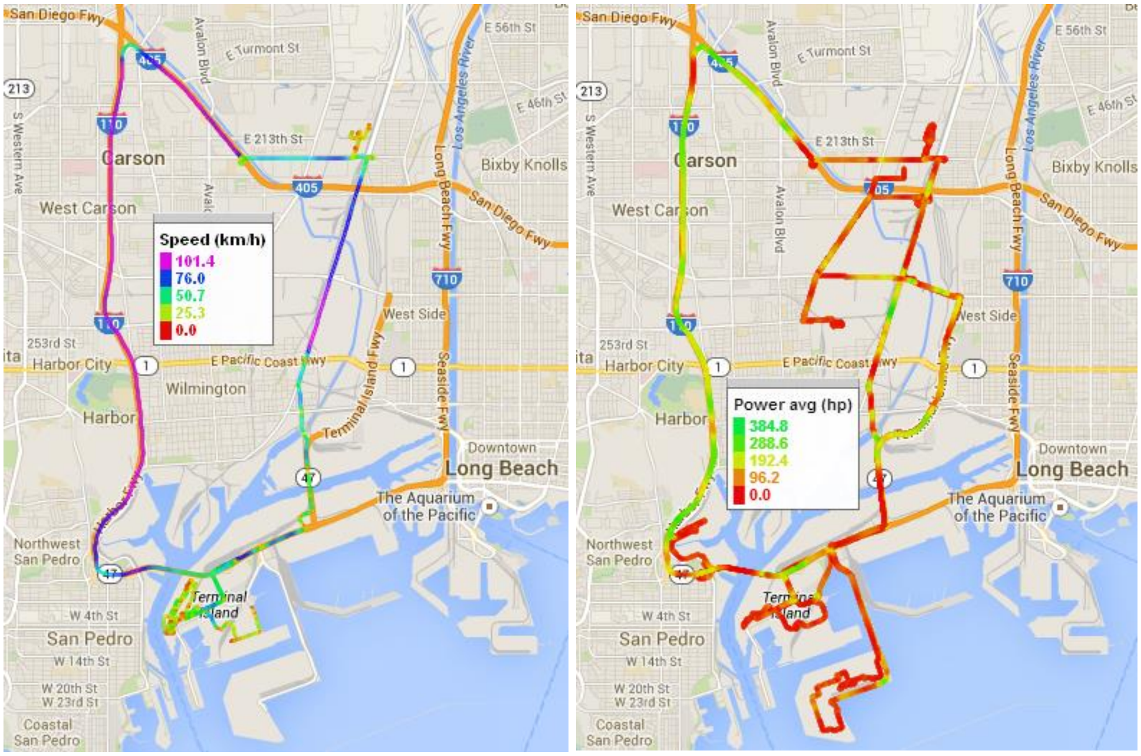


Figure 3 – Sample Results from Logged Data Analysis, Vehicle Speed and Engine Power

This analysis also allowed us to confirm how much time trucks spend on average in certain areas or operating conditions, for example do they idle for extended period of times during the day, do they shut off the engine for extended periods, do they wait long within potential Zero Emission geofences, etc.? These parameters are very important to determine how to best optimize energy usage for the concept. While the answers to those types of questions are very dependent on the drivers and the days, we found that trucks averaged about 2.5 hours idling and 1 hour in the key-off position a day.

We also calculated the distance travelled inside certain perimeters in order to determine possible distances that would need to be covered in full electric mode. Since battery capacity is limited by packaging and weight constraints this data is crucial to identify possible recharging patterns and help guide the definition of a battery management strategy.

Since we could not record the weight of the containers transported by the customer trucks monitored we developed post-processing macros in Visual Basic to estimate the weight of the complete trucks for each drayage trip: by looking at the power produced by a truck's engine in a consistent section of road for multiple trips we were able to correlate power usage to vehicle weight on a normalized scale ranging from bobtail tractor to tractor with heavy container.

After post-processing the logged data was ultimately displayed in tables as illustrated below to extract the desired information:

Total Per Shift	
Time (hr)	8.25
Distance (mi)	81.31
Idle (min)	172
Key Off (min)	104

Complete Port Region	
Time (hr)	4.86
Distance (mi)	28.41
Idle (min)	110
Key Off (min)	80

Terminal Island	
Time (hr)	3.65
Distance (mi)	20.23
Idle (min)	89
Key Off (min)	53

Power (hp)	Time (% of time spent in port region)
50	87.8
100	5.9
150	2.4
200	1.4
250	0.9
300	0.6
350	0.5
400	0.3
450	0.1

Speed (mph)	Time (% of time spent in port region)
5	73.8
10	6.6
15	5.3
20	3.6
25	2.1
30	1.7
35	1.7
40	1.6
45	1.4
50	1.0
55	0.6
60	0.3
65	0.3

Our original intention was to define a Zero Emission geofences that corresponds to Terminal Island. However, after looking at the GPS data we noticed a significant amount of truck operation on various docks that are not included in terminal Island. For example we noticed a region north west of the center of the island that seems to be used as a main chassis drop-off or pick-up area. We also noticed frequent activity on docks located north of Terminal Island. While most of the pick-up areas observed are inside Terminal Island, these observations will be instrumental when defining a detailed geofence for the demonstration of Zero Emission operation. The geofences used to determine the mode of operation can be altered very easily if necessary, to adapt to changing infrastructure or mission requirements.

The work described above helped us identify the most representative route for a full day of operation. The corresponding virtual duty cycle was created in our simulation environment will be used for the remainder of the project as the reference cycle for energy optimization, performance benchmarking, etc. Since the detailed altitude data collected previously did not cover the full area of operation of the customer trucks, we repeated the altitude data collection procedure along the full route identified as our target cycle during the last reporting period.

All final simulations and optimization were therefore performed using this fully accurate road profile, which is representative of the typical daily operation of drayage trucks in the ports of Los Angeles and Long Beach.

Task 3 - Concept Selection and Hardware Development

3.1 The goal of this sub-task was to evaluate and select driveline and chassis components based on their impact to the complete vehicle performance and energy management. This work consisted of selecting the correct size for the diesel engine, the electric motor and energy storage system, and auxiliary components.

The demonstrator truck builds upon Volvo's second generation proprietary parallel hybrid driveline with Integrated Starter-Alternator Motor (ISAM). Several candidate driveline and chassis components were evaluated and this configuration provided the best compromise for the usage of the truck in terms of cost/weight/performance. Table 1 shows the hybrid components which were selected for the demonstrator vehicle configuration based on previously reported analysis on their predicted impact to the complete vehicle performance and features.

Table 1 – Hybrid Driveline Components

Electric Drive System (EDS)	Energy Storage System (ESS)
PM Synchronous Motor 80kW Continuous; 150kW Peak 295 lb-ft Continuous; 880 lb-ft Peak	600VDC, Li-ion Energy Optimized ~10kWh usable
Internal Combustion Engine (ICE)	Transmission
EPA2010 Compliant 11-liter, 325 - 405hp Peak Torque 1,560 lb-ft	Automated Manual (AMT) 12-speed, Direct Drive 1,920lb-ft Maximum Input Torque
On-Board Charger	DC/DC Converter
10kW output max 240 – 480VAC input	600-to-24VDC 270A max

In order to maximize the Zero Emission range of the vehicle with a fully charged battery, the team used results from simulated sensitivity and energy balance analyses reported previously to identify the biggest losses in drayage operation, as seen in Figure 4 below.

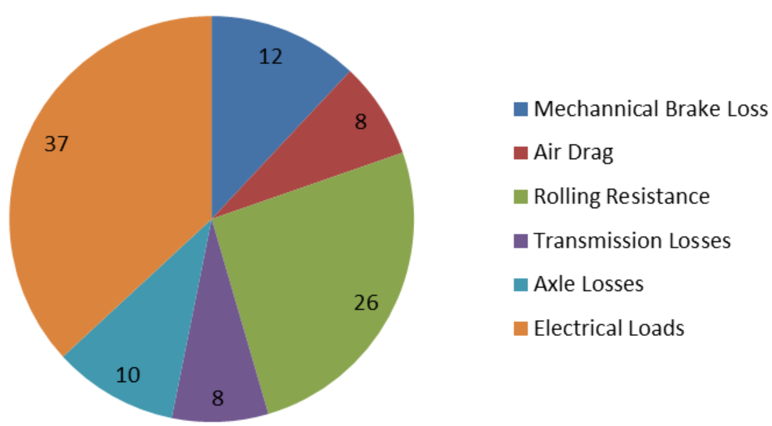


Figure 4 – Typical Energy Analysis for Drayage Truck on Local Haul Cycle

Based on this analysis a few solutions were included in the concept in an effort to attempt to minimize rolling resistance, electrical loads and other parasitic losses. They consist of the following.

3.1.1 Rolling Resistance

Based on third party analysis of drayage operation shown in Table 2, over 75% of the drayage trip transaction types (trip ”legs”) would only require two axles (in-lieu-of three) on the tractor unit to carry the load. Furthermore many “loaded” trips, depending on the container weight, may not require all three axles on the tractor as well.

Table 2 – Drayage Transaction Types

Transaction Types		Entry			
		Bobtail	Bare Chassis	Empty on Chassis	Load on Chassis
Exit	Bobtail	Bobtail in Bobtail Out	Chassis in Bobtail Out	Empty in Bobtail Out	Export in Bobtail Out
	Bare Chassis	Bobtail in Chassis Out	Chassis in Chassis Out	Empty in Chassis Out	Export in Chassis Out
	Empty on Chassis	Bobtail in Empty Out	Chassis in Empty Out	Empty in Empty Out	Export in Empty Out
	Load on Chassis	Bobtail in Import Out	Chassis in Import Out	Empty in Import Out	Export in Import Out

= Loaded Transaction (8 of 32 possible = 25%)

A 6x2 axle configuration with liftable “pusher” auxiliary axle was chosen to reduce axle losses. The auxiliary axle is only deployed when dictated by vehicle load requirements, thereby reducing rolling resistance when only utilizing two axles instead of three.

As an additional benefit this non-driven ”pusher” axle can provide a more stable vehicle and better load distribution than the more common non-driven ”tag” (rear-of-drive axle) 6x2 axle configuration.

3.1.2 Parasitic Electrical Consumption

Exterior lighting is one of the main electrical loads on a day-cab tractor especially if the headlamps are used, which is expected to be typical in drayage operation. Therefore the team is partnering with Grote to demonstrate a high-efficiency LED light engine, which will replace the incandescent baseline headlamps. Table 3 below shows a breakdown of the energy savings possible with this retrofit.

Table 3 – Power Saving Potential with LED Headlamp

Lamp Function	Baseline (Incandescent) Current [A]	Baseline (Incandescent) Wattage at 12.8V	LED Current [A]	LED Wattage at 12.8V	Power Saved per Function [W]
High Beam	11	140.8	4	51.2	89.6
Low Beam	9	115.2	3	38.4	76.8
Front Turn	4.2	53.8	1	12.8	41.0
Front Park	0.5	6.9	0.2	2.6	4.4
Totals	**24.7**	**316.7**	**8.2**	**105**	**211.8**

A photovoltaic module was also fitted to the roof deflector of the vehicle in order to harness solar energy to supply to 24V components, hence minimizing parasitic consumption of electrical energy while stored in the hybrid battery. Testing confirmed that up to 30% of the idle current consumption under stationary operation in a zero emission geofence could be offset with this approach.

3.1.3 Cooling System Optimization

All new components are liquid cooled, which requires additional cooling circuits that cannot benefit from ram air as they need to be frame mounted. These could become significant electrical loads and therefore impact the overall Zero Emission range of the vehicle. The team developed an integrated thermal management plan in order to maximize energy efficiency of the complete vehicle. The layout selected was designed to maintain each system in its optimal operating temperature window while maximizing the use of waste/residual heat and minimizing energy consumption of the pumps and fans.

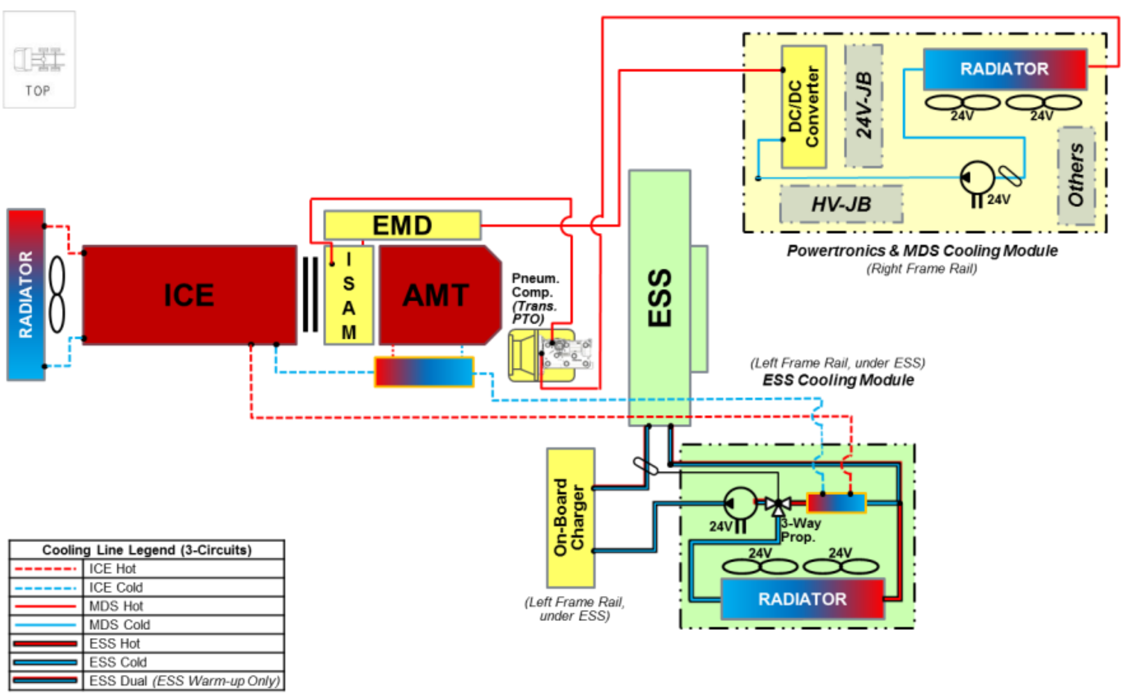


Figure 5 – Integrated Thermal Management, final layout

The energy consumption of the hybrid cooling system was optimized through detailed performance analysis of the proposed layout. The results of this investigation showed that the temperature of the coolant exiting the radiators could be lowered by approximately 3% in worst case ambient conditions compared with the baseline configuration, and that air flow into the radiators would be significantly improved, by 49% just by separating the two radiators, compared with the baseline stacked radiator configuration provided by the supplier. Further potential air flow improvements were identified, and were included in the design of the new cooling brackets, for example add sealing between the box and the inlet grille, better packaging layout to improve air flow between components, with potential improvements in air flow through the radiator up to 90% compared with the baseline configuration. These improvements allow a significant reduction in fan demand engagement, which reduces energy consumption and noise emissions of the cooling package. Reducing the electrical consumption of the electrical pumps and fans is key to maximizing the range of pure electric operation of the concept vehicle with the battery selected. The final cooling system layout shown in Figure 5 leverages lessons learned and experience from previous hybrid studies and customer field tests performed by Volvo.

Validation testing of the cooling system during the summer 2015 confirmed that the improvements made to the cooling system were indeed significant. The pumps for both circuits provide sufficient flow at minimum duty cycle during normal hybrid or full electric operation, and all hybrid components are maintained within their nominal temperature range with the fans either off or running at their minimal duty cycle. This translates into extremely low 'idle' power consumption, hence preserving energy from the battery for propulsion and maximizing the range of full electric operation.

3.1.4 Cabin Heating

Another key take-away from the detailed development of the cooling system layout was that the integration of the cabin heater into the hybrid cooling circuit would not yield the benefits originally anticipated. The lower average coolant temperature of the hybrid systems, compared with the temperature of the engine cooling system, would require a redesign of the cabin heat exchanger core in order to provide similar cabin heating performance. In order to minimize cost and complexity increase for this concept and secure timely completion of the demonstration we decided to implement 'point of use' electric heaters, which will be used during engine-off operation. The system simply consists of two off-the-shelf 24V ceramic heaters installed directly in the ventilation ducts of the cabin to provide heat in the most critical vents (driver feet and windshield diffuser) when the defrost switch is activated. This approach is successfully used in passenger cars today, and our experience in this project proved that cost and complexity of this implementation were minimal.

3.1.5 Weight Reduction

The hybrid components add approximately 1,700 lb. to the truck when compared to a typical drayage tractor. In order to prevent this curb weight increase from reducing payload capacity or increase energy consumption, the team explored changes that could

offset the weight of the hybrid components. Several lightweight alternatives were identified in the list of customer options available for production such as aluminum fifth wheel, aluminum fuel and air tanks, aluminum cross members and wheels, and aluminum rear carrier housing. The incremental cost associated with these modifications was factored into the final cost/benefit calculation for the concept. The most significant weight reduction came from the conversion from a 6x4 to a 6x2 axle configuration, the switch from double wheels to wide base single wheels on the rear axles, and the optimization of the fuel tank size thanks for drayage operation.
All of these improvements added up almost exactly to the weight of the hybrid components, and all were included in the demonstrator vehicle. The curb weight of the final vehicle is approximately 18,000 lb., which is slightly higher than the base vehicle as a result of the weight increase from other vehicle improvements including aerodynamic enhancements and modification of auxiliary systems. This first concept vehicle does however contain several redundant systems for reliability reasons and does not accurately represent the exact weight of a mature hybrid vehicle.

3.1.6 Aerodynamic Improvements

The energy analysis of the drayage duty cycle illustrated in Figure 4 above indicates that aerodynamic drag causes considerable energy losses in the overall operation despite the very low average speeds. This is most likely due to the poor aerodynamic configuration typically observed on drayage tractors, as represented by our baseline truck specification. Even though aerodynamic performance improvements would not contribute noticeably to extending the range of the vehicle operating at low speeds within a Zero Emission geofences, they are an integral enabler in the hybridization of the vehicle as follows

- They contribute to reduced fuel usage in the complete cycle, which allows to downsize the fuel tanks as described above
- They free up more kinetic energy for recovery through the hybrid system, which helps make the overall energy balance of the cycle more positive

Several improvement areas were identified in a review of the baseline vehicle, and their potential weight/aerodynamic drag trade-off was assessed to determine which should be deployed on the concept vehicle. The aerodynamic enhancements that were installed on the vehicle include new bumper ground effects, new wheel well enclosure, front chassis fairings, wheel covers, D-shaped fuel tank, recirculation shield around the front radiator, cab side deflectors, low profile roof marker lights, removal of the air horn from the roof, and an adjustable roof fairing.

3.2 The goal of this sub-task was to perform system-level simulations to optimize the technology combinations and determine the optimal driveline topology. Different selections of diesel engine and electric motor were evaluated together with the transmission concept for overall torque and power performance. This evaluation also helped determine the size and type of energy storage system needed for the final concept. Volvo relied heavily on system-level simulations for this part of the project to facilitate the selection and refinement of the concept, as well as to prepare for the calibration and optimization of the demonstration vehicle.

The complete vehicle simulation team used the proprietary Global Simulation Platform (GSP) for concept studies and optimization of the whole truck. GSP uses Matlab/Simulink to model the complete vehicle, the road and environment and the driver within one simulation. GSP hence forms an ideal platform to analyze and design the truck based on a system approach rather than a component approach. In the early phase of the project simulations were performed with a simpler PHEV vehicle model to establish basic energy analysis as well as component sizing, especially the battery sizing.

Generally we have a very high confidence in the simulation work because simulations have been validated with road tests; however the drayage vehicle operates at very low speeds where model calibrations and assumptions have not previously been verified as thoroughly. The team therefore initiated a campaign to correlate the GSP models with road test for low speeds like those expected in drayage application. Several low speed tests were performed in 2013 with the fully instrumented Base truck on a test track (see base truck in Figure 9). Test conditions included constant speeds, coast down, deceleration in gear, acceleration and braking.
A virtual duty cycle was created for the same track using altitude data recording with a barometric pressure sensor during the test campaign. GSP simulations were performed with the base truck model on this cycle for the same low speed operating conditions, and the data obtained from the road test was analyzed and compared with the simulated values. We found that the correlations between GSP and road test were consistent throughout the speed range. Hence we could conclude that the model was valid for low speeds as well as far as constant speed performance is concerned.

3.3 The goal of this sub-task was to design systems to allow the auxiliary components to operate independently of the diesel engine to provide seamless performance of the critical vehicle functions such as power steering and brakes.
The selection of layout and components focused on providing a robust solution while minimizing the increase in complexity or predicted production cost. Table 4 below shows the auxiliary systems which were selected for the final demonstrator vehicle configuration based on previous experience from concept studies and customer field tests performed by Volvo.

Table 4 – Auxiliary Systems

Power Steering	Air Compressor
Electro-Hydraulic (EHPS) 24V Electrically driven gear pump	Dual 636cc 2-cyl Air Compressor Layout Engine & Transmission Mounted
Cab Heating	Air Conditioning
Electric heaters inserted in cab vent ducts and electric defrost added to windshield	24V A/C compressor in parallel with standard compressor, electric condenser fans

3.3.1 Electro-Hydraulic Power Steering

The power-steering concept consists of an Electro-Hydraulic system which replaces the baseline mechanically driven gear pump. This solution not only provides power steering

seamlessly between Hybrid and Zero Emission operation, it also provides energy savings compared with the conventional engine-driven system thanks to active hydraulic flow control.
A prototype was delivered in January 2014 and was installed in the vehicle. It operates seamlessly between hybrid and full electric operation, and test drivers have been positively impressed with the overall performance of the system compared with conventional mechanically driven power steering pumps. Even though the system is an early prototype and hasn't been optimized specifically for drayage operation it has demonstrated minimal power consumption at idle conditions, which confirms the assumptions made during the selection of this technology.

3.3.2 Air Compressor

In 2013 we confirmed that the predicted performance of our proposed system matched the demanding requirements of the drayage application due to frequent stops and trailer connections. We selected a 636cc, 2-cylinder compressor currently available on our commercial trucks as a base for the auxiliary system. A countershaft power take-off speed ratio of 1:1 to 1.3:1 was selected in order to achieve compressor speeds similar to those observed on the standard engine-mounted compressors in the range of engine speed typical of cruise conditions regardless of gear ratio at a given vehicle speed, as shown in Figure 6.

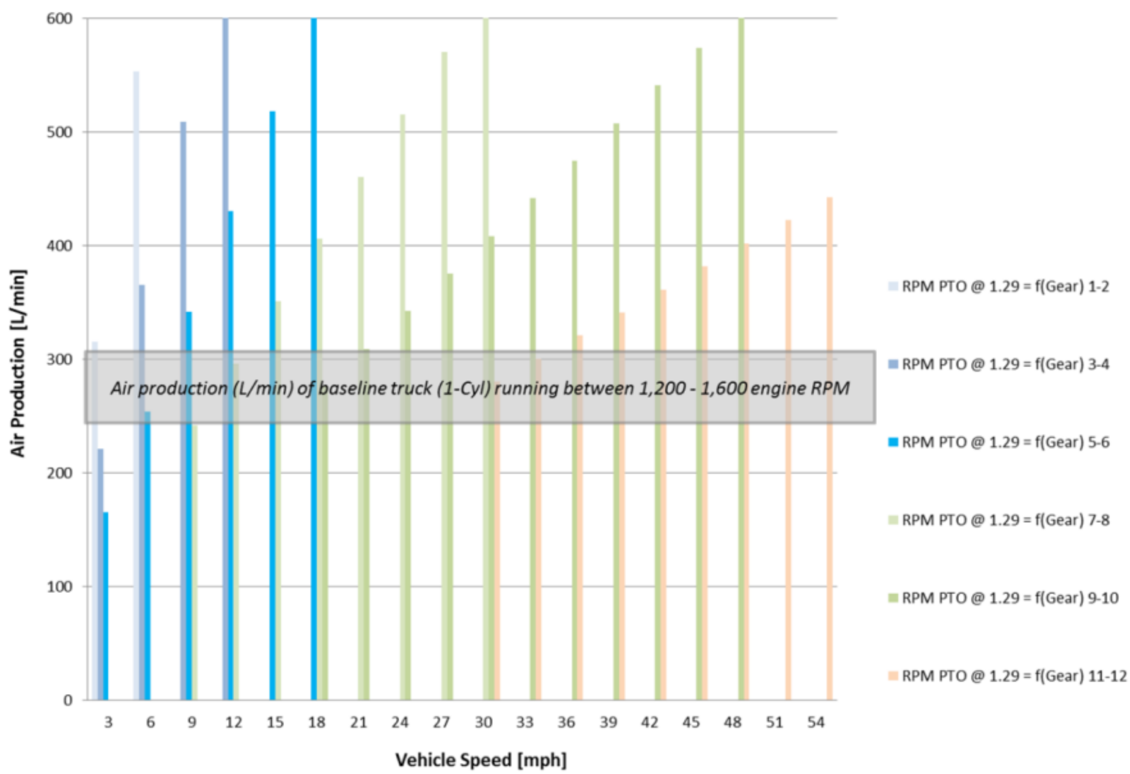


Figure 6 – Air Production Calculation for Transmission-Mounted Air Compressor

The design of the auxiliary air compressor system was completed and all components were fabricated and installed in 2014. The concept vehicle was equipped with this auxiliary compressor system and tested during the commissioning phase. Initial results indicate that the compressor is sized and geared adequately to produce ample amounts of air during full electric operation. We are however still working on improvements to the control strategy of the dual-compressor system and troubleshooting high noise concerns in the circuit.

The truck's hybrid control strategy also contains a fail-safe function that automatically cranks the engine when system air pressure reaches a critically low level while operating in Zero Emission mode. This allows the engine driven compressor to refill the air tanks before the low air pressure causes the brakes to lock up. When full air pressure is reached, typically within less than a minute, the engine shuts down and full electric operation is resumed.

3.3.3 Cabin Cooling

In order to provide seamless air conditioning to the driver while inside or outside of a Zero Emission geofences we selected a hybrid dual-compressor solution, illustrated in Figure 7. The goal of this approach was to minimize the number of new components as well as utilize the existing A/C system whenever possible in order to minimize electrical energy consumption. The components highlighted in blue are the only additions required to the existing system. An agreement was established with a supplier in 2013.

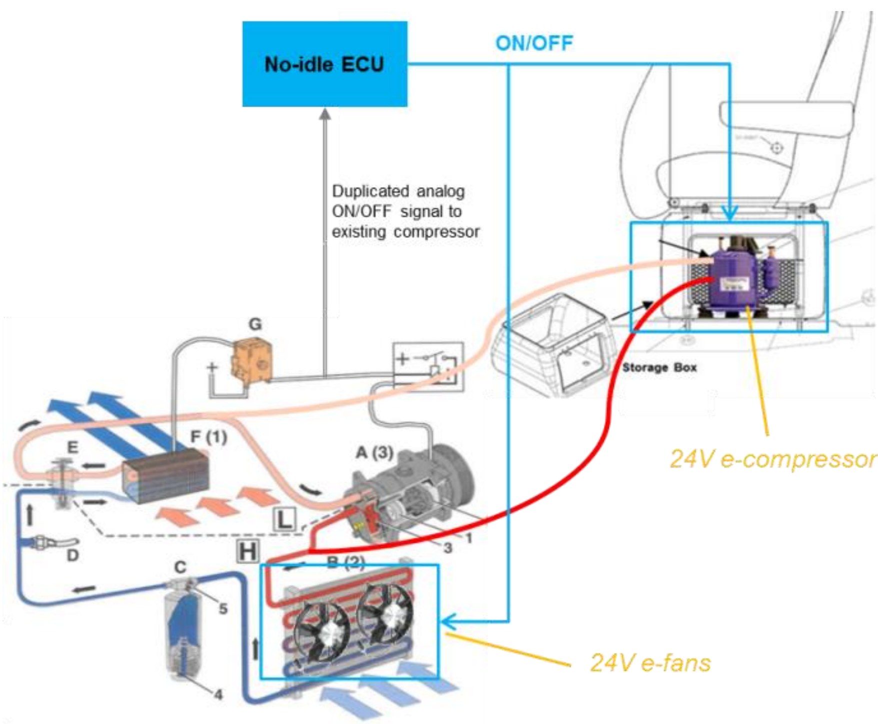


Figure 7 – Illustration of dual-compressor air conditioning system

Since the electric part of the A/C system is only required to provide cooling performance while in geofences we were able to downsize the compressor. This allowed us to select a 24V component which does not require additional power electronics, and can easily be packaged within the cab.

The complete system was tested on bench in 2014 and showed very positive energy consumption and cooling performance figures. The components were assembled by the supplier upon completion of bench testing, and the unit was installed in the vehicle.

Unfortunately we have encountered difficulties during the implementation of the system in the complete vehicle and have therefore not yet been able to verify the performance of the downsized unit under normal vehicle operating conditions. This delay is only due to errors in the plumbing modifications on the refrigerant circuit, and we do not anticipate any issues with the performance of the modified circuit since it was confirmed by the bench tests.

3.4 The goal of this sub-task was to investigate the potential benefit of re-optimizing the combustion efficiency for the selected engine to match the operating points demanded by the PHEV system to improve overall thermal efficiency at specific load points and reduced emissions. Comprehensive simulations were performed to evaluate this concept while designing the energy management strategy for this truck, and it was found that with the hybrid power split strategy selected in this project the engine is already operating at a near-optimal duty cycle.

When in hybrid mode the electric motor typically assists during vehicle launch and gear changes, and the engine provides power when the vehicle is operating under more steady conditions. Moreover the implementation of full electric operation in geofences with a high percentage of time spent at idle of very low vehicle speeds eliminates the most inefficient operating conditions of the combustion engine. This strategy results in a higher average thermal efficiency for the engine while in hybrid mode without requiring a recalibration of the combustion system that would require re-certification of the powertrain for criteria pollutant emissions.

3.5 The goal of this sub-task was to implement manual controls to engage and disengage all-electric mode on demand. After all-electric driving and when the battery is depleted to the lowest allowed state of charge, the truck was required to switch to a charge sustaining hybrid mode, which would allow the diesel engine to provide power for propulsion, but still take advantage of energy regeneration during braking and coasting.

The simulation studies performed early on in the project identified significant potential benefits from the implementation of geofences to determine Zero Emission areas. This approach led to the need to develop of a new driver interface, the Energy Management Panel (EMaP), which allows the driver to define multiple geofences where Zero Emission operation is required or desired, and request pure electric operation if needed while outside of pre-defined geofences. The EMaP concept is illustrated in Figure 8.

The EMaP was initially developed as part of an academic partnership between Volvo and Penn State University, where three teams of students have completed the concept as their senior design projects on developing parts of the concept during 2014.

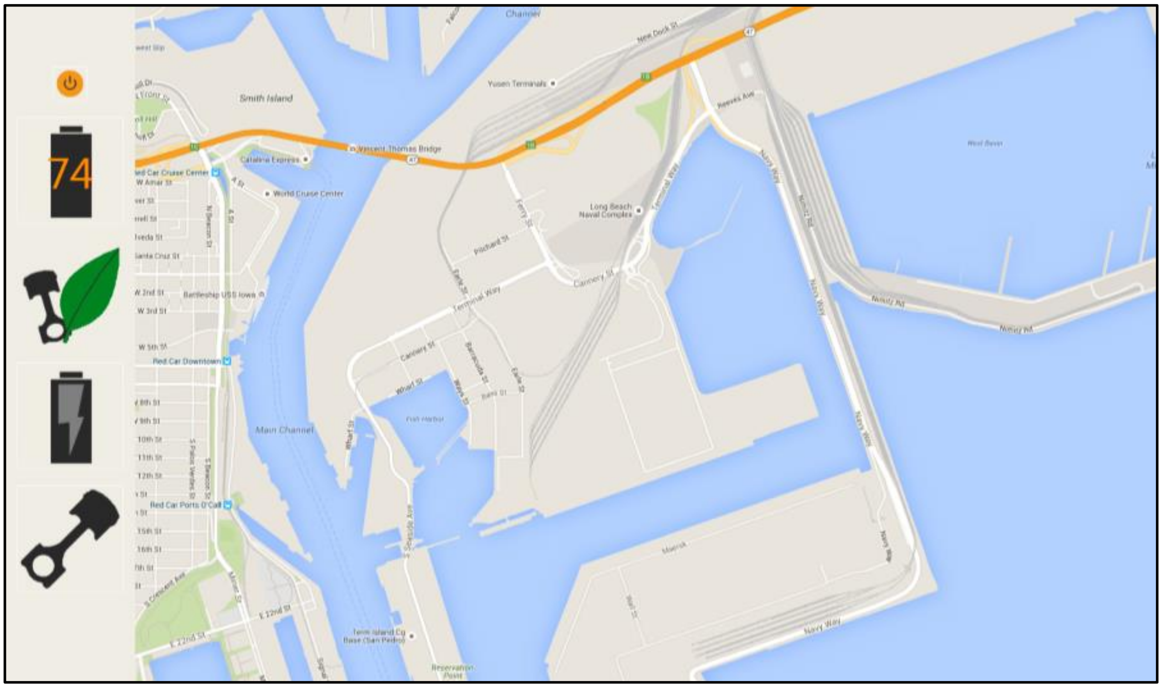


Figure 8 – Implementation of the Energy Management Panel (EMaP)

The system is implemented using a rapid prototyping approach in order to minimize cost and allow for quick development loops of the functionality. It consists of a Microsoft tablet mounted on the dashboard which communicates with the embedded driveline software using proprietary datalink messages. A simple hardware-in-the-loop rig was also built to allow the development of this system in parallel with the retrofit of the prototype truck.

The EMaP provides a robust control platform to switch between three possible modes of operation:

- By default and when outside of all geofences the truck operates in hybrid mode with the combustion engine providing power to the wheels, assisted by the motor if needed. Regenerative braking and coasting are always enabled.

- When approaching a predefined Zero Emission geofence the truck operates in a hybrid mode with active battery charging, using the electric motor to quickly recharge the battery with energy produced by the combustion engine. This mode ensures that the state of charge of the battery will be high when the truck enters the upcoming zero emission geofence.

- Whenever inside of a Zero Emission geofence the truck switches to full electric operation. The battery size and energy management strategy selected should allow the truck to remain in full electric mode for up to several hours e.g. while waiting for a container in a marine terminal as typically observed in drayage operation.

The EMaP system was installed and tested in the vehicle during commissioning of the hybrid driveline and complete vehicle validation activities. We verified that the truck functionality met the initial requirements:

- Requests for specific modes of operation are sent by the unit to the embedded driveline controllers depending on the position of the vehicle and of the geofences defined. This allows the vehicle to switch between modes automatically as the vehicle moves between geofences, with seamless performance and no action required from the driver

- The driver can also select specific modes of operation (Hybrid or Zero Emission) using the manual override controls on the EMaP screen. The current battery charge is also displayed on the screen to help the driver determine which mode of operation to select.

Although this wasn't implemented during the project execution due to limited resources, this same interface could also serve as an interactive display to keep the driver informed of key vehicle performance criteria, coaching tips to encourage more energy efficient driving behavior, etc.

Task 4 – Control System Development

4.1 The goal of this sub-task was to optimize the system controls to provide best energy efficiency under drayage-type operation.

The approach chosen was to minimize the overall energy usage of the plug-in drayage truck through optimization of the torque distribution between the combustion engine and the electric motor in order to use of the most efficient energy source at all times. In early 2014 the software development team successfully ran test versions of the engine and transmission software packages on Hardware in the Loop (HiL) rig. Software development for all new features was completed in 2014, including the strategy defined through simulations for the energy management and the modified controls required for the improved cooling package.

4.2 The goal of this sub-task was to develop control algorithms for the electrified auxiliary components and integrate them into the overall energy management strategy for the plug-in hybrid driveline. This work was intricately linked to the development of software and calibrations described in the previous sub-task.

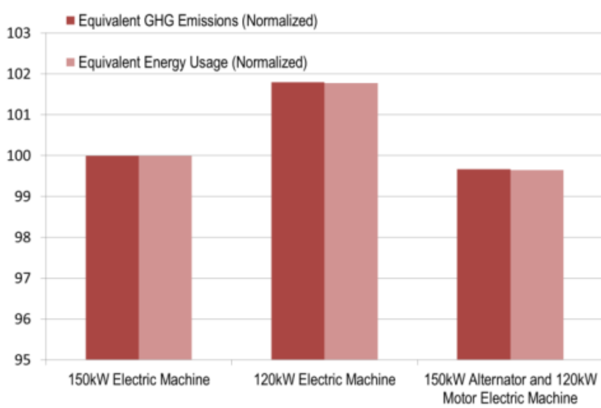
In order to minimize risk for this project, most of the prototype auxiliary systems designed by suppliers were required to have their own controls including energy optimization and diagnostics. This allowed for simpler electrical & electronic interfaces with the Volvo proprietary controls and quicker commissioning of the complete truck.

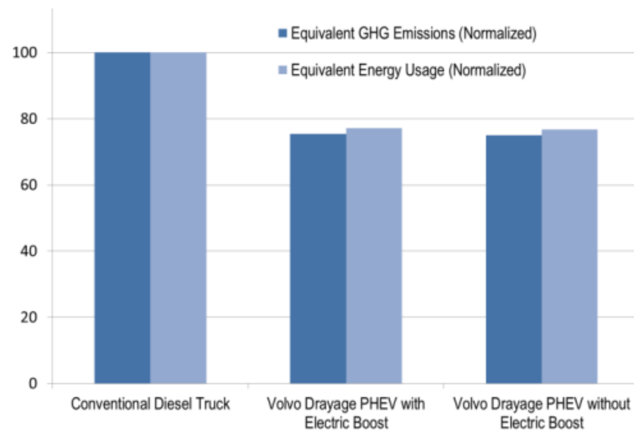
As described in Task 3 all auxiliary systems tested performed as expected and the energy consumption was lower than that of the baseline systems.

4.3 The goal of this sub-task was to use virtual tools to aid in the development of system calibrations optimized for reduced energy usage in port drayage applications. Since the vehicle model of the plug-in electric hybrid drayage truck contained the same algorithms as the software in the concept truck, the behavior of the virtual vehicle emulated that of the real truck and provided an ideal platform to assess the impact of any given parameter on the complete truck, regardless whether the change was external (road grade, vehicle weight) or internal (varied distribution between electric motor torque and engine motor torque).

This virtual platform was used to evaluate and pre-optimize calibrations for reduced energy usage in the duty cycles developed previously to represent port drayage operation. It was also used to analyze the sensitivity of this calibration against duty cycle, driver behavior, container weight, etc.

The charts below illustrate the types of results that can be obtained with this method, analyzing the impact on greenhouse gas emissions and fuel use of peak electric motor power (on left) or the impact of using the electric to boost while in hybrid mode or only to capture kinetic energy (on right).





The calibrations were tested and refined using this virtual tool and constitute Future testing in the vehicle can therefore focus on fine-tuning drivability.

The resulting calibrations of power distribution, energy management and cooling system control were then implemented in the prototype truck's engine and hybrid control units, providing a very robust starting point to initiate testing. Validation activities confirmed that the performance of the truck in all modes was satisfactory, but some calibrations were refined based on feedback from the test drivers to further enhance the behavior of the hybrid driveline.

Task 5 – Component Validation

5.1 The goal of this sub-task was to develop or adapt an energy storage system specific to the plug-in hybrid driveline demonstrated in this project. A detailed analysis was performed in order to select the system size and control strategy which delivers the targeted range for pure electric operation without prematurely sacrificing battery life, comply with the battery manufacturer's recommendation for charge/discharge strategies, etc.

The energy analysis studies performed through simulations delivered information on the duty cycle of the battery as a result of the plug-in hybrid drayage utilization. This allowed the engineers to evaluate the requirements on component performance, and provided a basis for a few adjustments to the application window of the battery, for example we were able to increase the window of usable energy without jeopardizing durability thanks to a limited energy throughput. We also determined that the energy throughput resulting of drayage operation required only minimal cooling of the battery, which allowed us to minimize energy consumption by the pumps and fans with calibrations optimized for drayage trucks.

5.2 The goal of this sub-task was to compare various electric charger solutions and select one that is best suited for the port drayage application. The selection of an appropriate charging solution is directly linked to the intended usage of the truck, and can considerably affect the potential energy consumption and emission reduction of the concept. Therefore Volvo leveraged this demonstration opportunity to engage with the prospect end-users of the vehicle and survey the key requirements to securing operational effectiveness of a plug-in hybrid heavy duty drayage truck. In 2013 the engineering team interviewed the equipment manager for a large drayage fleet to capture key prerequisites and expectations on vehicle charging from the grid from a user's perspective.

The on-board charger selected for this proof of concept allows demonstrating plug-in charging at 'medium' power levels i.e. up to approximately 10kW at 480VAC. This should allow a refill from mostly depleted to mostly full battery in 30-45 minutes during the driver's break. The system is also designed to be flexible so that we can take advantage of the existing electric vehicle charging station infrastructure at 240VAC, although charging power at these lower voltages will be limited with this first concept vehicle. A prototype was delivered in August 2014 and installed in the concept truck.

Due to limitations with the prototype component the compatibility with 240VAC charging stations could not be demonstrated on this truck.

5.3 The goal of this sub-task was to develop a Verification Plan to validate that the plug-in hybrid electric driveline meets the requirements developed in Task 2. Verification activities did not focus on component durability for this concept truck, but rather on validating that the performance matches design requirements.

Number	Check Item	Description	How To Measure
1	Maximum Engine Torque	The maximum engine torque should correspond to the engine torque limit as set in the project	Accelerate a fully loaded truck from zero speed to cruising speed.
			Climb a steep slope.
2	Maximum Powertrain Torque	The maximum powertrain torque (defined as the sum of engine torque and motor torque) should be as set in the calibration.	Given that we have no electric boost, the maximum powertrain torque should be the same as the maximum engine torque. Hence the maximum engine torque test is applicable here as well.
3	Boost	Check the values of electric boost when SoC >=SoC target	Make sure that the motor torque is zero even when a fully loaded truck is accelerating from zero using full power.
4	Cold Start	Start with cold IC engine?	If the IC engine is cold, it should not crank and the electric system should be the first to kick in. The engine should crank once certain conditions are met.
			The conditions for exiting the electric only condition induced by the cold IC engine are ....
		Start with cold battery?	
		Other cold start conditions?	
		Cold start at low SoC?	How does the vehicle start if it is cold and the battery is at or below SoCWinLow?
5	Cranking	Cranking the vehicle from stationary	This is the normal process of cranking the engine. It will likely be tested by Jason before we take the truck out on the road.
		Cranking the engine using the clutch after an electric start	Test the cranking of engine by the electric machine after the vehicle starts from zero speed (low speed)
			Crank of engine from electric motor at high vehicle speed like exit from a geofence.
			Crank the engine from electric motor because of low SoC in an electric only zone.
6	Boost Pressure	Check values of boost pressure. Check values of turbo speed and corresponding limits.	This can be done during other operations of the truck. We just need to ensure that the boost pressure is within the expected range.
7	Move to electric only geofence	Transition into an electric only geofence when SoC<SoCtraget	Check how the electric only mode is activated.
			Check what happens to the engine speed when the transition happens.
		Transition into an electric only geofence when SoC>=SoCtarget	Check how the electric only mode is activated.
			Check what happens to the engine speed when the transition happens.
8	FEA before geofence	Transition into FEA from no geafence. Monitor the rate of increase of SoC inside the FEA region.	Check how the vehicle transitions into the FEA mode.
			Check how quickly the battery is charged.
			Check the effect of the FEA mode on vehicle performance.

A detailed test and verification plan was developed to confirm proper operation of all features in this complex vehicle. It was created using the system level requirements that were developed in the start of the project, and each test mirrors a technical requirement.

The snapshot to the left shows an excerpt of the verification checklist that was used by the system verification engineers.

The tests were completed shortly after the demonstration held in Greensboro in late July.

Task 6 – Prototype Vehicle Build

6.1 The goal of this sub-task was to build a prototype vehicle to validate the concept and designs selected for the port drayage plug-in hybrid electric demonstrator.

The parallel hybrid driveline system used by Volvo consists of a battery pack, an electric machine, electrified auxiliary components and power electronics. The overall layout and length of the integrated hybrid driveline is similar to a conventional powertrain, which allows for seamless installation into the Mack Vision day cab Class 8 chassis. A conventional chassis was identified in the engineering test fleet, which exactly matched the specification developed for our base vehicle, see Figure 9 below. This truck was secured for this project and was used as a “base truck” for the hybrid conversion.

Figure 9 – Base Vehicle before conversion

It became available to the team mid-2013 and was used for baseline testing and instrumentation troubleshooting. Having access to the actual base vehicle early in the project resulted in a 4 to 6 month time saving: it allowed the team to conduct detailed testing to allow thorough correlation with the virtual concept truck in the low-speed operation unique to drayage trucks as described in sub-task 3.2 above. This freed up additional time and resources to perform non-critical upgrades to the vehicle as described in sub-task 3.1, which helped maximize the overall feature level of the demonstrator and impact of this proof of concept.

The team strived to use existing components whenever possible in the definition of this truck in order to reduce unique development efforts and maximize commonality with similar products. This approach should help minimize the incremental cost of the concept compared with the baseline drayage truck.

During the fall 2013 the vehicle was disassembled and the retrofit process started at Volvo Group Truck Technology's Vehicle Engineering facilities in Greensboro, NC. The engine was shipped to Volvo Group Truck Technology's Powertrain Engineering facilities in Hagerstown, MD where it was upgraded and prepared for the hybrid retrofit. The pictures included at the end of this section illustrate the work performed on the vehicle during the upgrades and hybrid conversion.

6.2 The goal of this sub-task was to perform virtual assembly of the chassis prior to the build of the vehicle to ensure optimal use of the space available when packaging all new components required for the plug-in driveline. These include electrical components as well as additional low-temperature cooling circuits. This critical step helped ensure that the wheelbase of the concept vehicle remained the same as that of typical drayage trucks in order to maintain maneuverability and payload capacity.

The base vehicle for this project was defined using fleet order information from existing drayage trucks. An average configuration was identified among the most recent orders of Mack Vision day cab tractors for this fleet, see Figure 10 below.

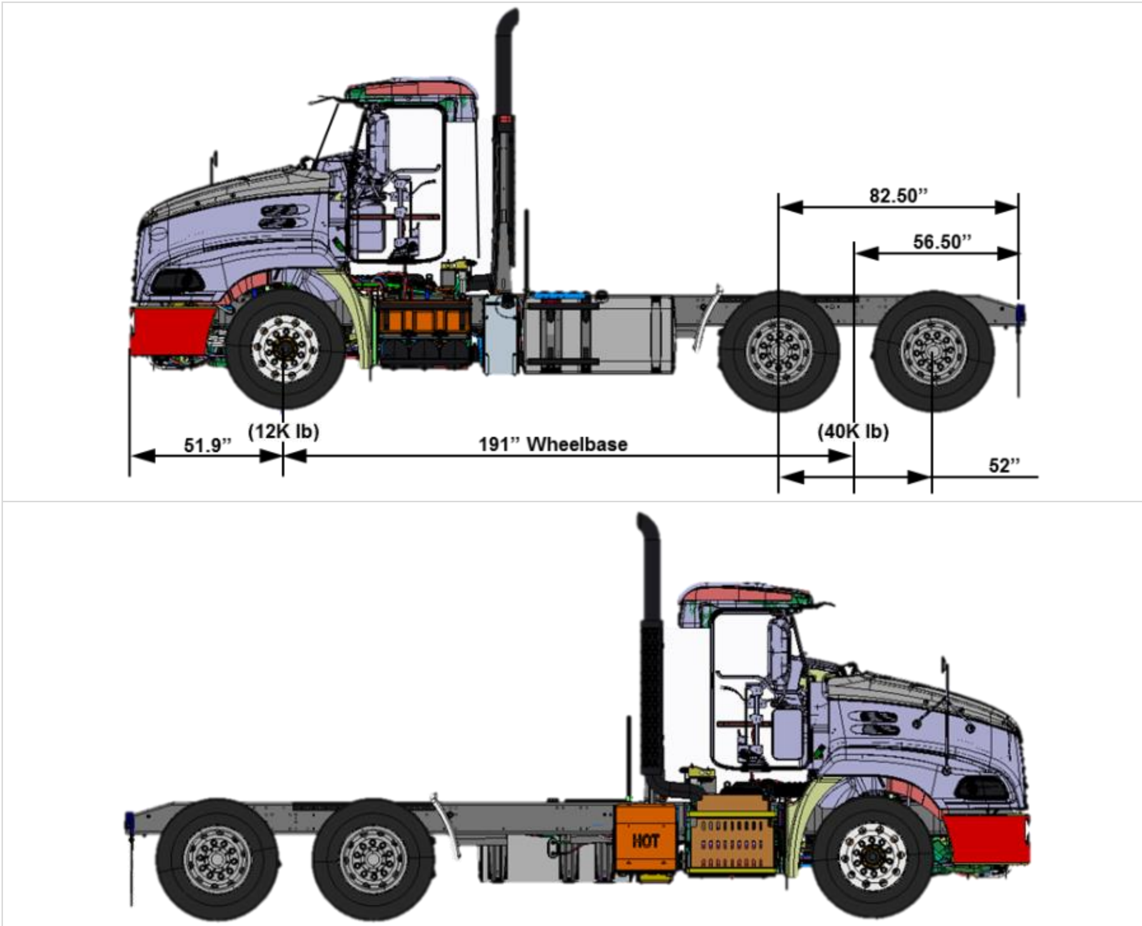
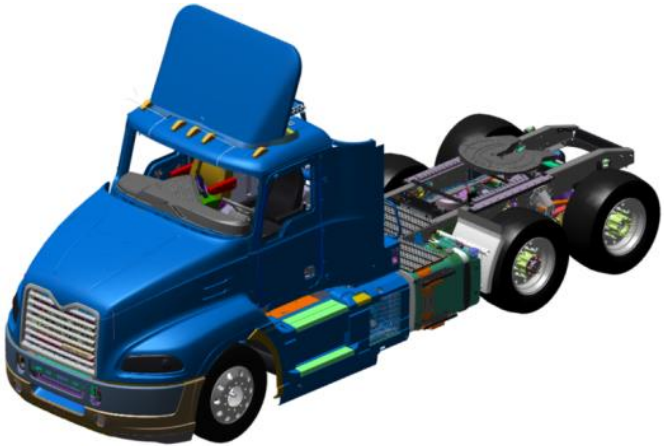
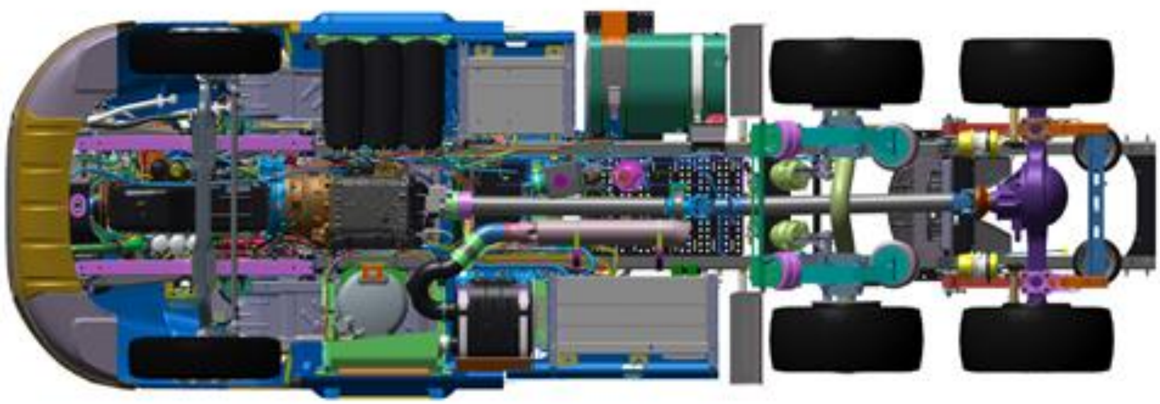


Figure 10 – Configuration of Baseline Vehicle

A detailed packaging study supported the integration of all new components and guided the development of a complete vehicle configuration with best trade-off when it comes to wheel base, weight increase, clearances, wiring, plumbing, etc.

The detailed virtual assembly was completed mid-2014 showing the final packaging proposal for all new components on the base truck shown in Figure 9. All interferences identified were resolved, and all new brackets required were fully designed in 2014. See snapshots of the final virtual assembly below.





Pictures of the truck during retrofit and upgrades:

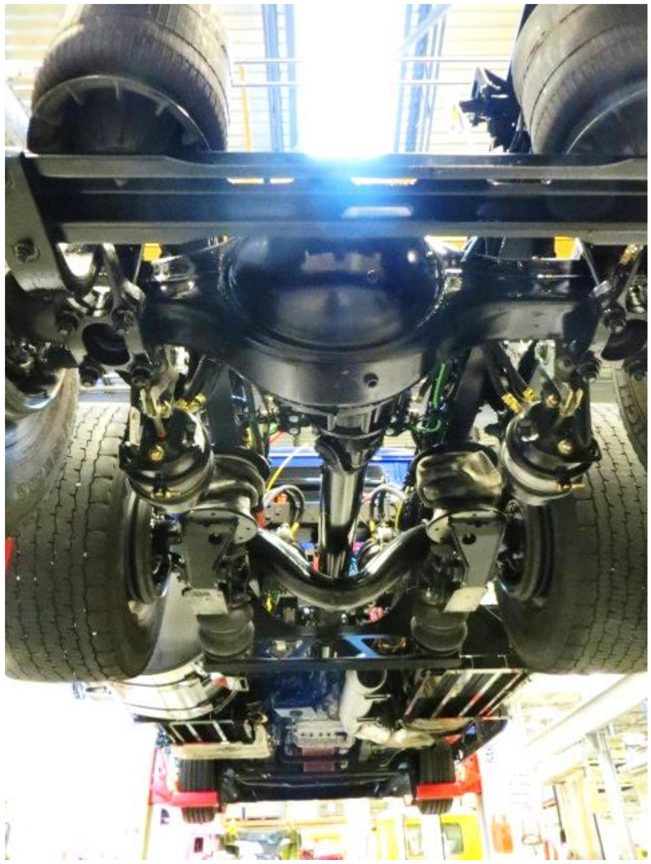
This picture shows the plug-in battery installed behind the cab.

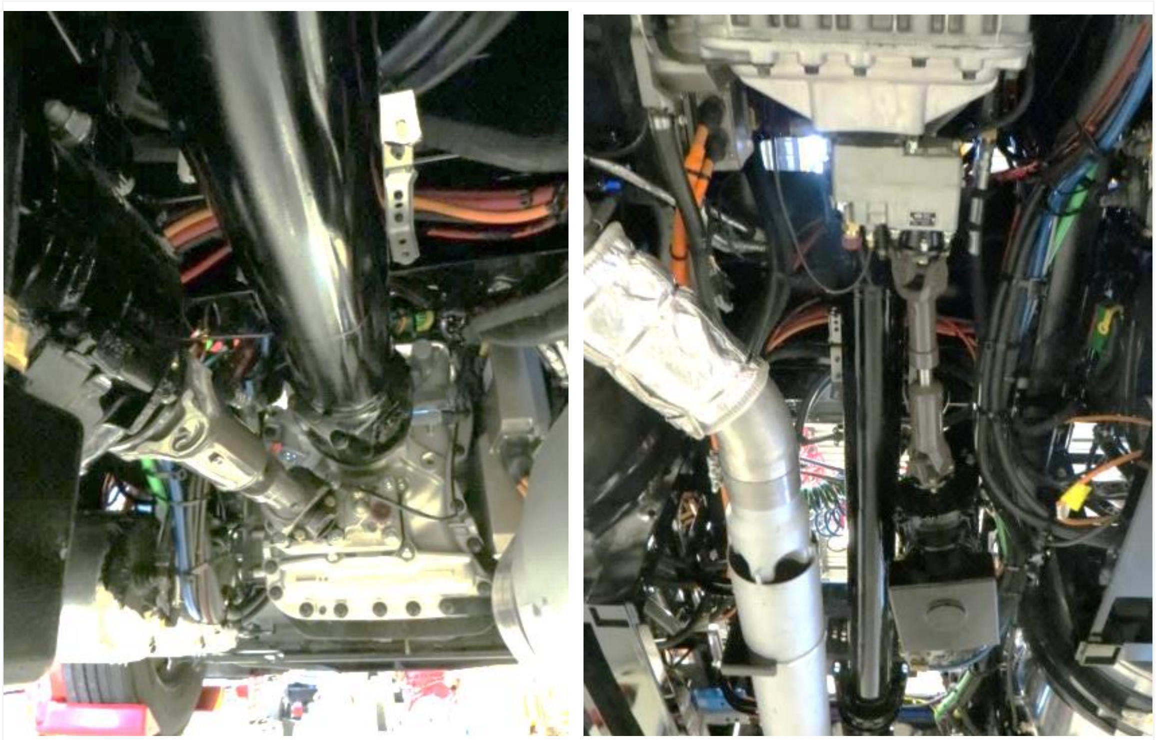
The new cab side fairings are also visible, which improve aerodynamic performance of the concept truck and thereby reduce energy usage in drayage operation.

These electric fans were added in order to provide airflow through the existing A/C condenser when the engine isn't running

A prototype EVSE was installed in the workshop to provide a 480V 3-phase connection. It will be used to recharge the plug-in battery using an on-board charger. The connector used is similar to IEC Type2.

The maximum charging power for this vehicle is limited to 10kW.





Commissioning of the prototype vehicle begun in late 2014 with the first engine re-crank test completed at the end of January –successful at first attempt. Commissioning of most systems was completed during the spring, in time for the final demonstration in July 2015.

Task 7 – Vehicle Testing and Demonstration

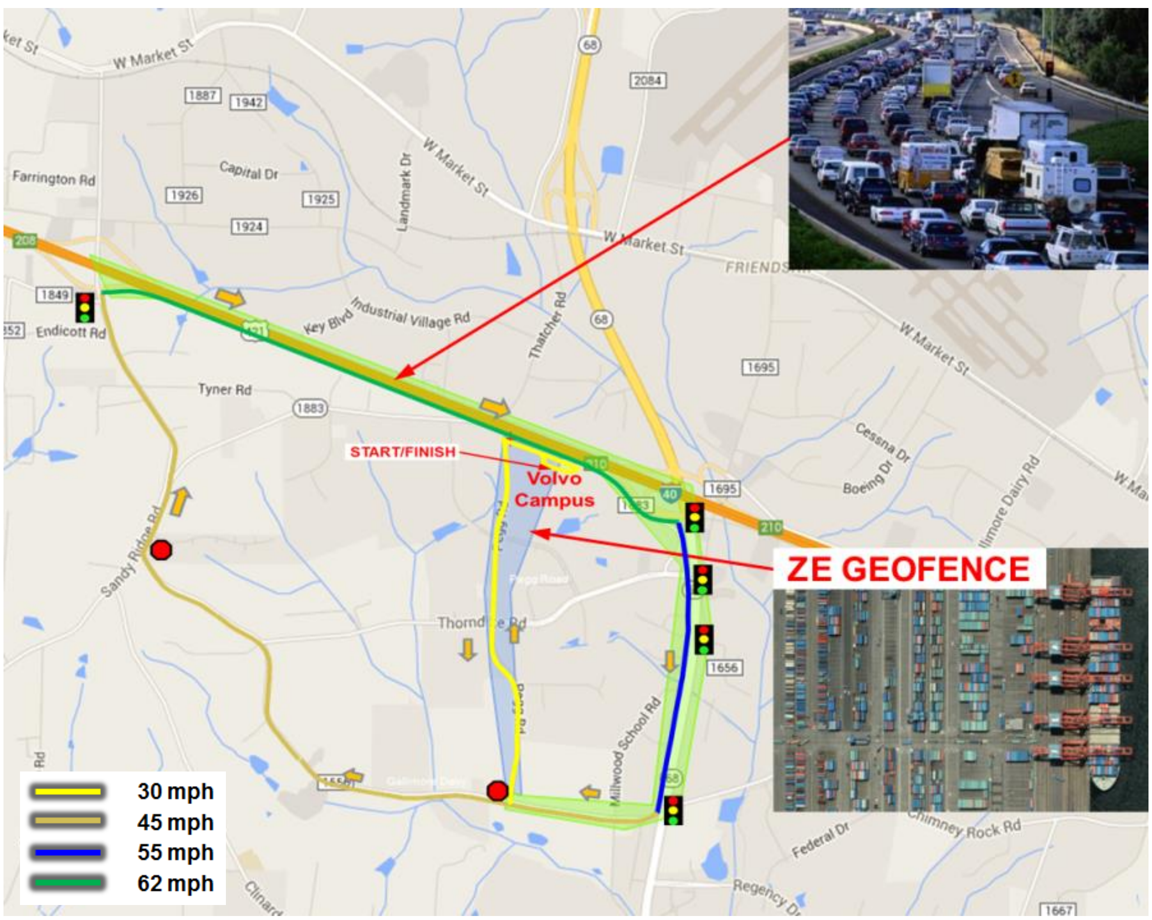
7.1 The goal of this sub-task was to present a working prototype plug-in hybrid truck and a first evaluation of the efficiency and emissions reduction potential of the technology. The performance of this concept vehicle should be benchmarked against a baseline port drayage truck using the drive cycle established earlier in the project. The performance evaluation should include comparative testing to quantify the change in fossil fuel consumption and criteria pollutant emissions.

Vehicle testing began as part of the commissioning phase, when all sub-systems were individually tested using engineering tools to force specific modes of operation. The following components were tested and verified this way: hybrid cooling pumps and fans, electro-hydraulic power steering, hybrid battery and motor, auxiliary air compressor, DC/DC converter, and EMaP system. All performed as designed.

Testing was limited prior to the final demonstration as a result of multiple delays experienced during the vehicle conversion and commissioning; however sufficient complete vehicle validation was performed to verify satisfactory gear selection behavior and shifting between hybrid and full electric modes. Although some calibration work was required to meet desired performance in both hybrid and full electric mode, automatic shifting of mode worked perfectly during the performance evaluation.

A final demonstration of the concept truck was held at Volvo's North American Headquarters in Greensboro, NC on July 29th 2015 with representatives from Volvo, South Coast AQMD and the Department of Energy. The meeting consisted of a detailed technical review of the demonstrator and a ride & drive event.

The route selected for the demonstration included all traffic conditions typical of drayage operation in Southern California as well as geofences defined to showcase the zero emission capabilities of the concept truck. The demonstrator successfully completed 4 consecutive runs on the route illustrated below with a gross combined vehicle weight of 44,000 lb. The total distance covered in the Zero Emission (ZE) geofence was approximately 2 miles out of a total distance of 9 miles per trip. The green geofence shown on the map illustrates the approximate distance covered while the battery is actively charged during hybrid operation, in anticipation of re-entry into the ZE geofence.



The vehicle is expected to use approximately 30% less fuel than the baseline truck in drayage operation, and is designed to allow full electric operation whenever operating in a marine terminal in the ports of Los Angeles / Long Beach.

A few pictures of the final vehicle during performance evaluation are included below.


MACK TRUCKS, Inc.

Task 8 – Study of Electrified Road Systems

8.1 The goal of this sub-task was to conduct a study to identify the feasibility of further developing the PHEV developed as part of this project to enable a wayside power connection. The wayside power connection would provide a dynamic link to the electrical grid that would enable the vehicle to derive the entirety of its motive power from an off-board energy source. The study should focus on the dynamics of the vehicle-track relation and the electrical requirements including infrastructure, durability and safety considerations.

A paper study on the feasibility of expanding the capabilities of the plug-in hybrid concept developed as part of this project was performed and delivered in June 2015 as an addendum to the quarterly progress reports. The executive summary from that study is included below for reference:

"Electrification of commercial vehicles is being investigated as a possible solution to reducing environmental impact of freight transport; unfortunately most energy storage systems have less energy density than liquid fossil fuels and which will limit the range of operation of the vehicles. For instance a battery with enough capacity for long distance transports would result in a substantial cost and weight increase of the vehicle, hence reducing payload capacity and overall transport efficiency. An alternative approach consists of continuously transferring energy from the road to the vehicle while it is moving, which is referred to as an electrified road system (ERS) in this study. A network of ERS connecting key transportation hubs would allow most of the distance to be driven using electricity from the grid, with the remaining distance driven on energy from an efficient combustion engine or from a smaller energy storage system optimized for shorter routes.

This report provides an overview of known ERS technologies to transfer energy from the road to the vehicle, and an analysis of their societal value. It also describes the impacts of a large-scale ERS implementation on various industry stakeholders as well as on technology choices for electric vehicles. A charging infrastructure for EV's is a long term investment for society, probably with the same perspective as railways, and choices made now may impact vehicle technologies in the following decades.

Multiple technologies exist, of varying levels of maturity, which can be combined to build an electric road system. Even though road bound solutions were introduced more recently than overhead alternatives they should now be regarded as a viable technology. Regardless of the choice of technology there are solutions that address the common concerns of safety and robustness.

The total cost of a given ERS implementation on society should however be a key consideration in the choice of technology since it can vary dramatically –see section 6. Vehicle costs are the primary driver of the total cost of implementing a fully electric road transport system in a case study focused on Sweden. In this study road bound ERS is found to be by far the cheapest solution because cars can also benefit from it, thereby significantly reducing the size requirement of batteries and need for stationary fast charging stations."

3. TRAINING AND PROFESSIONAL DEVELOPMENT

The frequent discussions and workshops held during the planning and kick-off phase of this project have allowed everyone involved to refresh and update their knowledge of industry standards as well as state of the art technologies regarding energy savings.

4. DISSEMINATION OF RESULTS

The customer truck data collection performed during this project to create a detailed drayage duty cycle with accurate altitude and performance metrics was critical to ensure that the system simulations could guide concept selections and serve as a virtual optimization platform.

We will therefore be publishing this detailed duty cycle to aid other projects focusing on improving the emissions and fuel use of drayage trucks in the ports of Los Angeles and Long Beach.

5. PRODUCTS

Inventions, patent applications, and/or licenses

One invention was filed to US Patent Office as a result of work performed in this project: PCT/US2015/026009, “Weight based aerodynamic deflector control”.

6. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

Organizations

The following organizations were involved with the project:

South Coast Air Quality Management District

Sponsor

Volvo Technology of America

Prime contractor & Project Management Office

Volvo Group Truck Technology

Main locations of performance: Hagerstown, MD & Greensboro, NC

Powertrain Engineering is the Volvo Group Strategic Center for complete powertrain systems, components such as engines, transmissions and driven axles. This includes development, manufacturing, sourcing, partnership and installation service along with support in close co-operation with the customers. Volvo is one of the world's biggest manufacturers of heavy-duty diesel engines between 9 and 16 Liter. Volvo is also a major manufacturer of heavy-duty transmissions.

Vehicle Engineering focuses on integrating the driveline with the tractor while improving the overall efficiency of the complete vehicle. The following areas are covered by this project: Advanced Powertrain integration, Reduction of Parasitic Losses, Idle Reduction, Vehicle Systems and Modeling.

Total Transport Solutions Inc. (TTSI)

TTSI operates a fleet of drayage trucks in the California South Coast area, and was selected by the project team as a key partner in this project. They supported the instrumentation of a few target fleet vehicles to collect detailed operating data. They also helped to determine the technical requirements applicable for the selection of an appropriate charging solution for the drayage plug-in electric application.

7. IMPACT

Impact and contributions of the project

This project contributes to increased focus and awareness on fuel economy and emission reduction of heavy duty vehicles.

Impact on the development of the principal discipline(s)

Previous experimental studies of hybrid electric heavy duty vehicles in similar duty cycles have demonstrated fuel savings of 5% to 20%. This project is expected to exceed these efficiency improvements thanks to the use zero-emission operation.

The complete vehicle simulation team uses the Volvo proprietary Global Simulation Platform (GSP) for concept studies and optimization of the whole truck. GSP uses Matlab/Simulink to model the complete vehicle, the road and environment and the driver within one simulation. GSP hence forms an ideal platform to analyze and design the truck based on a system approach rather than a component approach. The component models of advanced concepts developed during this project will be available to the designers in the future. This will allow the designers to look at their components from the system perspective. This will lead to more collaboration and development of highly integrated vehicles.

Impact on other disciplines

This project uncovered multiple potential synergies between parallel technical areas such as electromobility and Intelligent Transport Services.

Impact on the development of human resources

This project has helped creating new paths and connections between Volvo's North American and European engineering divisions. This helped speed up the transfer of skills and technology in the area of electromobility.

The approach chosen for this project relies heavily on virtual development, which requires new colleagues with these critical skillsets to be added to the local project team. A requisition for a first new hire was submitted during last quarter.

Impact on infrastructure

This project supported the submission in 2013 of a new proposed standard for charging interface of heavy vehicles: SAE J3068. The concept truck showcases components included in this proposal. The technical sub-committee had made significant progress at the time of writing of this final report, with several key players represented in the area of electrification across North America.

Impact on technology transfer

The industry's product development and advanced engineering communities are expected to benefit from such a project. Sharing of knowledge with other external partners and customers will help increase the understanding and awareness of joint obstacles and opportunities, as well as facilitate dialogue. The joint evaluation and exchange of advanced concepts early in the development stages will most likely contribute to the launch of HEV or PHEVs to market sooner than before.

This project will demonstrate the benefits of hybridization and zero-emission capabilities of heavy vehicles in specific areas and types of utilization. This should help prepare the industry and various stakeholders and create a comfort level for such changes.

Impact on emission of criteria pollutants and GHG

This project took a well-to-wheel approach in order to estimate the greenhouse gas (GHG) emissions from Drayage vehicle. In this analysis we calculated the overall Greenhouse gas emissions resulting from mining, transportation, processing and utilization of resources for producing kinetic energy in the vehicle. The GHG emissions were measured in the form of equivalent CO2 emissions. This is because some gases like methane have a high greenhouse effect. While converting to equivalent CO2 emissions, the emissions of all gases are weighted as if the overall greenhouse effect is because of CO2 only.

The CO2 equivalent emissions from the grid power were obtained from the eGIRD database. Since this this vehicle is to be used in the Los Angeles Port area only, the values of CO2 equivalent emissions from the eGIRD database is equal to 0.339Kg/KWH. The CO2 equivalent emission from one gallon of diesel fuel is 12.725Kg/Gallon.

Based on these numbers we predict that the Drayage PHEV usage will result in GHG emission reduction of 25%.

We also analyzed the emission of NOx for the development of PHEV vehicle. Volvo has developed advanced models for engine and emission components that can accurately predict the emissions from the engine and the effectiveness of aftertreatment components in reducing NOx. However, the development of such models requires detailed engine testing and compiled models of engine software. The control system for the engine for the Drayage PHEV project was built specifically for the project, and project resources were not sufficient to create a compiled model for this unique software to make it available for simulations. This task will be performed in the next project.

We also found that although aftertreatment models have proven to be highly accurate when predicting emissions on long haul highway vehicles, their accuracy in a vehicle duty cycle featuring low speeds and frequent start and stops is not as well quantified. Because of the above limitations, we can only provide a conservative qualitative analysis of NOx emissions from simulations performed at this point of time. Our general prediction is that the overall NOx emissions, measured in units of volume or weight per mile, will be reduced drastically but that the NOx emissions measured in g/bhp-hr may increase in a PHEV as compared to a conventional vehicle. The overall emission reduction is a result of the much lower fuel use, but the potential increase in brake specific emissions is due to a variety of factors: the frequent restarts of the engine are a new challenge when it comes to controlling engine-out emissions, cooling down of the engine and aftertreatment components during zero emission operation can result in lower average NOx conversion levels in the SCR system, and depending on how the hybrid driveline is controlled the engine could operate in higher brake specific NOx output load points more frequently than the equivalent conventional powertrain.

Our future work will therefore focus on improving our analytical tools to better capture engine and exhaust aftertreatment component behavior under start-stop or low speed conditions. We believe that this will help identify robust strategies to control the complex plug-in hybrid energy management algorithms in order to maximize the emissions and energy benefits of the vehicle compared to its baseline.

Impact on society beyond science and technology

This project demonstrates new complete vehicle solutions that can offer significant benefits when applied to a specific duty cycle. This could lead to a change in policy making for the transportation industry, focusing on reducing real world emissions impact of the overall transport solution instead of focusing on individual technologies.

8. CHANGES/PROBLEMS

Changes in approach and reasons for change

As a result of significant delays encountered in the build of the concept truck the project was extended by 7 months to allow completion of all tasks in the original scope, with no change in the total cost or budget. The baseline and updated schedules are illustrated below.